COMEX: A COMPUTER MODEL FOR DESIGN AND OPTIMIZING MAGAZINES OF EXPLOSIVE MATERIALS

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ABSTRACT

COMEX (Computer model for design and Optimizing Magazines of EXplosive materials), was designed to examine resistance of magazines against blast and impact created by explosion of soil covered neighboring magazines. The input contains locations and structures of magazines, inhabited sites and roads. The effect of explosion is examined on the base of ESKIþMO tests' data and structure resistance of neighboring magazines. With safety considerations of magazines, roads and inhabited sites, the model computes maximum permissible mass of explosive (TNT equivalent). The model can treat over a hundred magazines in a ranch, designing configurations of new ranches or maximizing permissible storage in existing ranches, possibly by emptying some of the magazines.

1. GENERAL

The need to store explosive materials is a problematic issue, faced by both heavy industries and military organizations all over the world. Explosive materials are generally stored in multi-magazine ranches in order to provide easy and fast access during loading\unloading tasks. There is no way to prevent an accidental explosion in a single magazine, but it is necessary to separate magazines to distances that prevent sympathetic explosions of several magazines. It is important however, especially in small countries, to reduce ranch dimensions in order to keep low cost of land, maintenance and security.

The planning of storage in a ranch is a complex task since one has to consider safety versus storage efficiency. In order to protect population in the ranch area and its periphery and to avoid sympathetic explosions of neighboring magazines, safety rules and models are applied. The limitations of storage are defined in terms of either minimal distances between objects or maximum permissible storage capacity for a given configuration.

The software tool COMEX (Computer model for design and Optimizing Magazines of EXplosive materials) was constructed to assist in planning and analyzing storage of explosives. It integrates safety rules and computations of resistance to blast created by explosions. This fast and efficient tool enables to recheck or plan storage of existing ranches with a large number of magazines and to reach an optimized storage capacity. If applied in a “trial &

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error” mode, the tool helps to plan an optimal ranch in a given site or choose the optimal site from several alternatives.

2. METHODOLOGY

2.1 Ranch Configuration - Input Data

To perform ranch analysis, it is essential to map magazines, inhabited sites within or outside the ranch borders and public routes in the periphery. Mapping refers to magazine types, locations, orientations and entrances. Each wall and roof classify up to a given type list.

2.2 Application of Safety Rules for Permanent Objects

The safety rules that refer to permanent objects, either limit the storage capacity of magazines or set a minimal distance permitted between each magazine and permanent objects like inhabited sites. The distances permitted are a function of explosive mass stored. These limitations are independent of neighboring magazines influences as long as there is no sympathetic explosion. COMEX can treat various sets of safety rules for different countries. It has also a default set obtained from ”NATO” rules (Ref. 1) and adapted to Israeli standard.

2.3 Computing Resistance of Magazines Structural Elements

Each magazine is a potential acceptor or donor. The interaction between magazines is therefore checked for each pair of magazines. This is performed by computation of dynamic strength of various reinforced concrete elements, based on the American Standard TM5-1300 (Ref. 2). Resistance and deflection angles are evaluated as a function of blast parameters **-** pressure and impulse, which are calculated on the basis of ESKIMO test (Ref. 3) data fitted to polynomial functions. The maximum attainable deflection is a function of the span, the thickness and the type of the element, as well as the amount and details of the reinforcement used. At a deflection corresponding to 2 degrees support rotation, the compression concrete crushes. This crushing results in failure of the element.

2.4 Permissible Explosive Storage Masses

The results of 2.2 and 2.3, applied to each pair of magazines, set for each magazine a maximum explosive's storage capacity in reference to every other magazine. These limiting mass values are configured in a squared matrix and are used to calculate permissible storage in magazines for each ranch configuration.

2.5 Optimization of Total Explosive Mass Storage In An Existing Ranch

In existing ranches, emptying a magazine may contribute to an increase of the total permissible explosive mass storage in the ranch. This occurs when the neighboring magazines that were limited by this magazine gain a storage capacity larger than the loss of the magazine to be emptied.

A parameter that scales the influence of a acceptor magazine on neighboring magazines’ permissible storage, may set a preference order of magazines to be emptied in order to increase the permissible storage of the ranch. The better configuration might thus reduce the total volume of magazines vacant for storage, but increase the total permissible explosive mass storage. The choice of a maximal volume configuration or a maximal explosive mass configuration is decided by the user, according to storage requirements.

3. PERMANENT LIMITATIONS

3.1 Principal Considerations

The main inhabited objects that have to be protected by appropriate distances, define three levels of limitations, two outside the ranch:

- Roads level, referring to randomly occupied areas outside the ranch
- Inhabited sites level, referring to continuously occupied areas or buildings outside the ranch
- Inside level, referring to inhabited buildings inside the fence of the ranch, as administration and laboratories.

For each of these levels, tables that consist of minimal distances permitted as a function of explosive mass are used (Ref. 1). The data depends also on the magazine's orientation relative to the specific object. All three levels are referred in the same manner: A theoretical closed line constituting the border of each level is defined. For inhabited sites and roads, the closed line circles the ranch, while the line resulting from inhabited sites is further from the road line. In the rare case of a site between the theoretical inhabited sites line and the fence around the ranch, inhabited site limitation will limit the magazines' storage.

3.2 Distances Between Magazines And The Theoretical Closed Line

The distance from each magazine to the theoretical line is evaluated by computing the shortest distance from eight representative points of the magazine (the corners and the wall centers) to the line (Figure 1).

3.3 Evaluation Of Permissible Storage Mass In Reference To Permanent Objects

The above shortest distance is compared to data in the safety rules tables. The permissible mass is computed by linear interpolation of the table data.

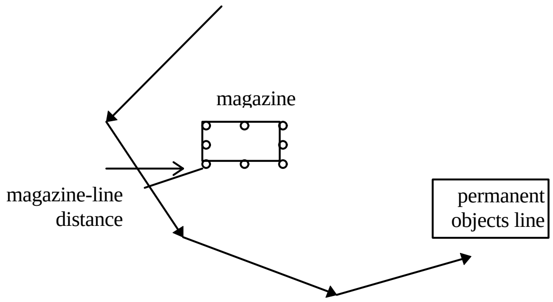

Figure 1: Theoretical line of permanent objects

3.4 Magazine Blast Orientation

The orientation of the blast from an exploding magazine is classified into three categories, corresponding to the wall that transfers the explosion. 'Wall with door' orientation is defined "Front", the opposite wall is defined as "Back" and side walls orientation is defined as "Side". The classification results from different resistance levels of

walls to blast, since the side and back walls are protected with soil. Figure 2 displays the three orientation zones defined.

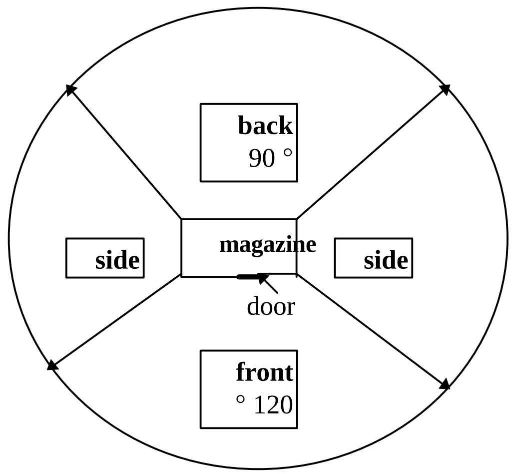

Figure 2: Orientation zones of a donor magazine

4. COMPUTING RESISTANCE OF MAGAZINES

4.1 Methodology

The main steps of the computation are:

- Geometrical computation of distances and directions of blast from donor magazine to the structural elements of the acceptor magazine
- Evaluation of pressure and impulse caused by explosion of a certain explosive mass at a given distance (based on ESKIMO data which was scaled to fit conventional magazine enforcement). The pressures are given in three principal orientations classified as "front" (door), "back" and "side". Topography influences are neglected.
- Given the incident pressure and impulse of the blast, dynamic reactions and deflection angles of the structural elements are calculated with structural parameters of the acceptor magazine as input. The calculation is executed by a routine based on Newmark equations (Ref. 4).

4.2 Computation Stages

The computation stages follow the methodology presented above.

4.2.1 Geometrical Computations of:

- Magazines' and walls' center

- Unit vectors perpendicular to walls
- Distances and directions from exploding magazine center to walls center. These are also the directions of pressure on the walls (Figure 3). The distance from the explosion center to the roof equals to the distance from the explosion center to the nearest point of the magazine.
- Computation of walls exposed to the explosion (Figure 3).
- Orientation of the acceptor magazine walls versus the principal blast pressure directions. This is evaluated by the calculation of the angle θ between the unit vector of the donor front (or back) wall and the pressure direction (Figure 3).

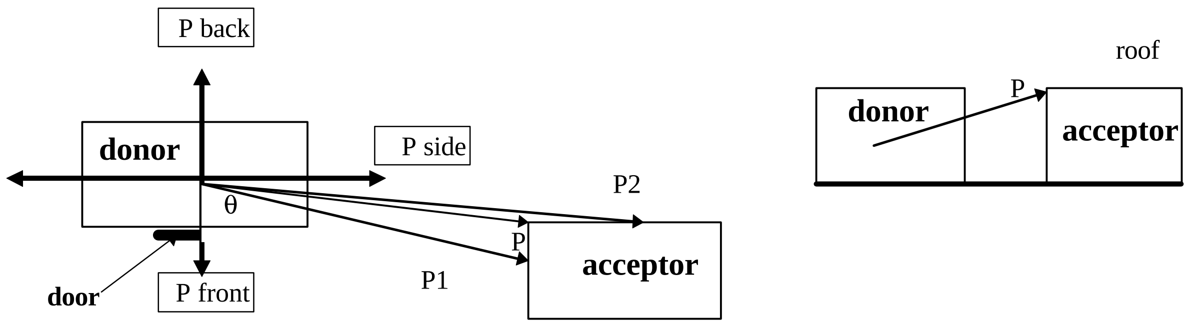

Figure 3: Exposed walls & pressure directions: horizontal and vertical sections

4.2.2 *Pressure Computation*

The pressure and impulse which result from the explosion of a stored equivalent TNT mass W are given by graphs of pressure and impulse as a function of scaled slant distance from explosion center, Z :

$$Z = R / W^{1/3} \qquad \text{R is the distance from explosion center} \qquad (1)$$

As was already mentioned, the pressure and impulse data are given in three orientations around the exploding magazine, with an assumed symmetry axis along the normal to the door wall.

A 3rd degree polynom was fitted to each graph. The logarithm of the pressure P and the scaled impulse I are polynomial functions of the logarithm of the scaled slant range Z as follows:

$$\log P = a (\log Z)^3 + b (\log Z)^2 + c \log Z + d \qquad (2)$$

$$\log I = e (\log Z)^3 + f (\log Z)^2 + g \log Z + h \qquad (3)$$

The coefficients derived from the ESKIMO data-fit, presented in the following table ,are for P (psi), I (psi×msec/ pound$^{1/3}$), Z (feet/pound$^{1/3}$).

	a	b	c	d	e	f	g	h
BACK	-0.28126	0.50443	-1.40623	1.87520	0.48946	-1.66011	1.15812	0.54852
SIDE	0.10660	-0.57514	-0.46007	1.76453	-0.13435	0.11136	-0.38183	1.10900
FRONT	1.66365	-4.60830	1.82884	2.19518	0.15374	-0.54927	-0.42555	1.69146

Since ESKIMO test magazines had a light front wall, we scaled the "FRONT" graph to fit enforcement of the front wall and barricade in front of the door. Figure 4 displays ESKIMO data for "SIDE" orientation and respective predicted values.

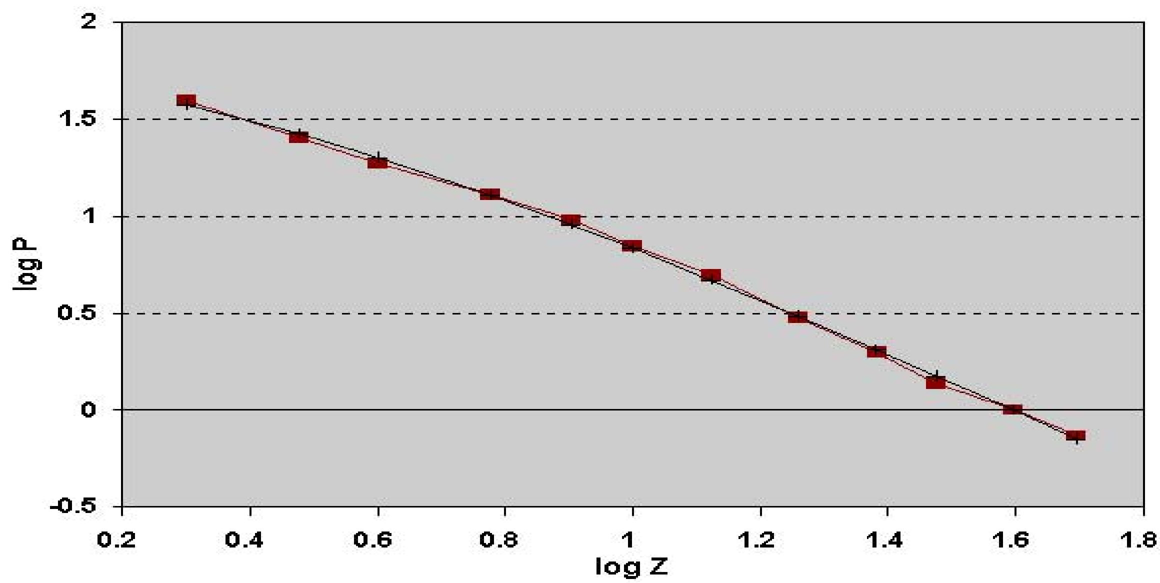

Figure 4: Polynomial fit of ESKIMO data for "SIDE" configuration

If the pressure or impulse direction differs from a principal direction, their values are evaluated on the base of two half-ellipses (Figure 5) that fit in the principal directions ESKIMO data orientations. The major half axes are the FRONT and BACK pressure (impulse) directions and the minor half axis is the SIDE pressure (impulse) direction.

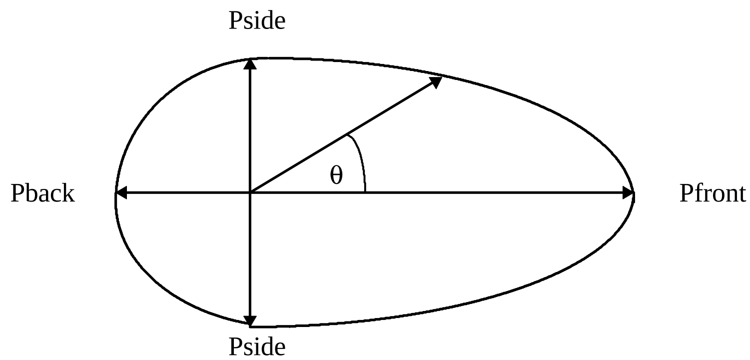

Figure 5: Orientation of blast pressure and impulse

If the explosion comes from FRONT/ SIDE sectors, then the pressure P and impulse I are:

$$P = [(P_{FRONT} \cos \theta)^2 + (P_{SIDE} \sin \theta)^2]^{1/2} \qquad (4)$$

$$I = [(I_{FRONT} \cos \theta)^2 + (I_{SIDE} \sin \theta)^2]^{1/2} \qquad (5)$$

A similar equation may be written for the BACK/ SIDE sectors.

The duration T of blast pressure incident on a wall is:

$$T = 2 I / P \qquad (6)$$

T he overall pressure and the time it acts on a given wall or roof are derived from the values calculated above:

- For a roof, the pressure taken into account is the incident pressure.
- For a wall, the pressure is composed of the reflected normal component and the incident tangential component.

4.2.3 Support Rotation Angles Computation

The computation of support rotation angle is based on Newmark energy equation (Ref. 4). The model of the structural elements consists of a point mass and a weightless spring with ideal elasto-plastic resistance. The equivalence of element mass, load and rigidity to a point mass and spring parameters is performed using tables of Ref. 5. The routine calculates also dynamic reactions and shear stresses when plastic deformation starts. Six static concrete or steel schemes are treated, four of which are beams and the other two are slabs. The output of the routine consists of parameters that enable to evaluate damage levels based on: ductility, deflection to span ratio and support rotation angles. The criterion for magazine failure is 2 degrees support rotation angle of a wall or a roof (Ref. 2).

5. PERMISSIBLE EXPLOSIVE STORAGE MASS

This stage involves computation of the maximum explosive mass allowed for a given magazine (i) relative to another (j). The maximum permissible explosive mass is reached when the support rotation angle reaches the 2-degrees threshold for one wall or roof.

The maximum value of explosive mass in magazine *i* which does not cause magazine *j* failure is the element Aij of the matrix described in 2.4. The permissible explosive mass is upperly bound by the magazine volume limit and by the permanent limitations.

6. RANCH TOTAL EXPLOSIVE STORAGE OPTIMIZATION

6.1 Independent Zones

When optimizing storage in ranches of large number magazines, one faces the difficulty of vast numbers of computations. One method to deal with this problem is to find , if possible, subgroups or zones of magazines, which don't influence each other's magazines. Within such a group, magazines are linked by limitations. This partition will result in a reduced number of computations since optimization is done now in each zone separately - any change of storage in an independent zone will not affect the other zones.

6.2 Sensitivity Parameter

The second method to reduce the number of computations defines a parameter that scales the limitations a magazine imposes (as a acceptor) on other magazines storage. The optimization of overall storage can be performed by emptying the magazines in a descending order of that parameter until a maximum overall storage is reached. This method avoids trying a very large number of configurations randomly.

The more a magazine is sensitive to neighboring explosions, the more it will limit the other magazines capacity. We defined a measure of a magazine's sensitivity to other magazines within an independent zone. For each magazine j:

$$aj = \sum_{i \neq j} \frac{1}{Aij} \tag{7}$$

6.3 Optimal Configuration

In the process of optimizing storage, the total permissible storage is calculated iteratively with magazines emptied in an order set by the sensitivity parameter. The iterations go on as long as explosive permissible mass gained is larger than the loss from emptying those magazines.

7. RANCH INPUT FILES

7.1 "Permanent Objects"

- The ” road file “ contains the coordinates of points which define the “road line”. The order of points corresponds to their order on the closed line which defines the road borders.
- The “Inhabited sites” file has the same format as the road file. It contains coordinates of the points constructing the line of inhabited sites and additional sites closer to the fence.
- Each office, institute, laboratory or any other working place inside the fence is defined in a separate file. Each file contains the coordinates of points defining the closed line corresponding to each of the places.

7.2 Magazines input

7.2.1 Magazine files

Each magazine is described in a separate file. Each file contains:

- the corners coordinates
- the door wall category
- the other walls categories
- the roof category

7.2.2 Walls & Roof Categories Files

- The walls' files contain the relevant input parameters to the computation of support rotation angles resulting from blast. The parameters are divided into groups:
- Dimensions
- Type of concrete and steel
- Location and quantity of concrete and steel
- Supports configuration

8. OUTPUT

8.1 Inter-magazine Limitations File

This file contains output data concerning each magazine and the limitations imposed on it by the other magazines as potential receivers or donors. The data contains for each magazine:

- Identity of acceptor magazines which limit explosive storage in the magazine while being a donor
- The maximum permissible explosive mass
- Distances between magazines involved
- The wall or the roof reaching first the 2 degrees support rotation angle

8.2 Ranch Optimized Configuration File

This file contains the same information as the above, for the optimal storage configuration, in which several magazines are kept empty. The file contains also the information about, independent zones in the optimal configuration.

9. EXAMPLE

9.1 Description

A weapon factory storage ranch consists of 23 magazines of two kinds. The magazines numbered one-hundred,

60 m' apart, are planned to store large amounts of raw explosive materials. The magazines numbered four-hundred, 44 m' apart, are planned to store small amounts of various finished products.
Three inhabited buildings limit the magazines' storage according to the "inside level". The two external lines are the roads level (inner line) and the inhabited sites level. The map of the ranch is displayed on Figure 6.

9.2 Results

9.2.1 Permanent Limitations

Under the safety rules, most magazines are limited to 150 ton. Limitations on magazines close to the inside level buildings are displayed in the following table:

raw materials magazines	limited explosive storage (ton)	products magazines	limited explosive storage (ton)
108	122	410	145
109	52	411	79
110	15	412	39
		413	15

9.2.2 Inter-Magazines Limitations

The magazines numbered one-hundred do not limit any magazine in the ranch. The magazines numbered four-hundred limit to ~112 ton the other magazines (not already affected by permanent limitations). They also interact between themselves and limit each other to 40 ton. The magazines' vulnerable element to collapse first in this configuration, is the roof.

9.2.3 Total Permissible Explosive Storage

The total permissible explosive mass with the above configuration full is 1463 ton. When emptying six magazines (402, 404, 406, 408, 410, 412), permissible explosive storage in each of the remaining magazines of the same kind increases from 40 to 95 ton. Total permissible explosive storage in this new configuration is 1562 ton, thus achieving a ~100 ton higher storage with 6 magazines less.

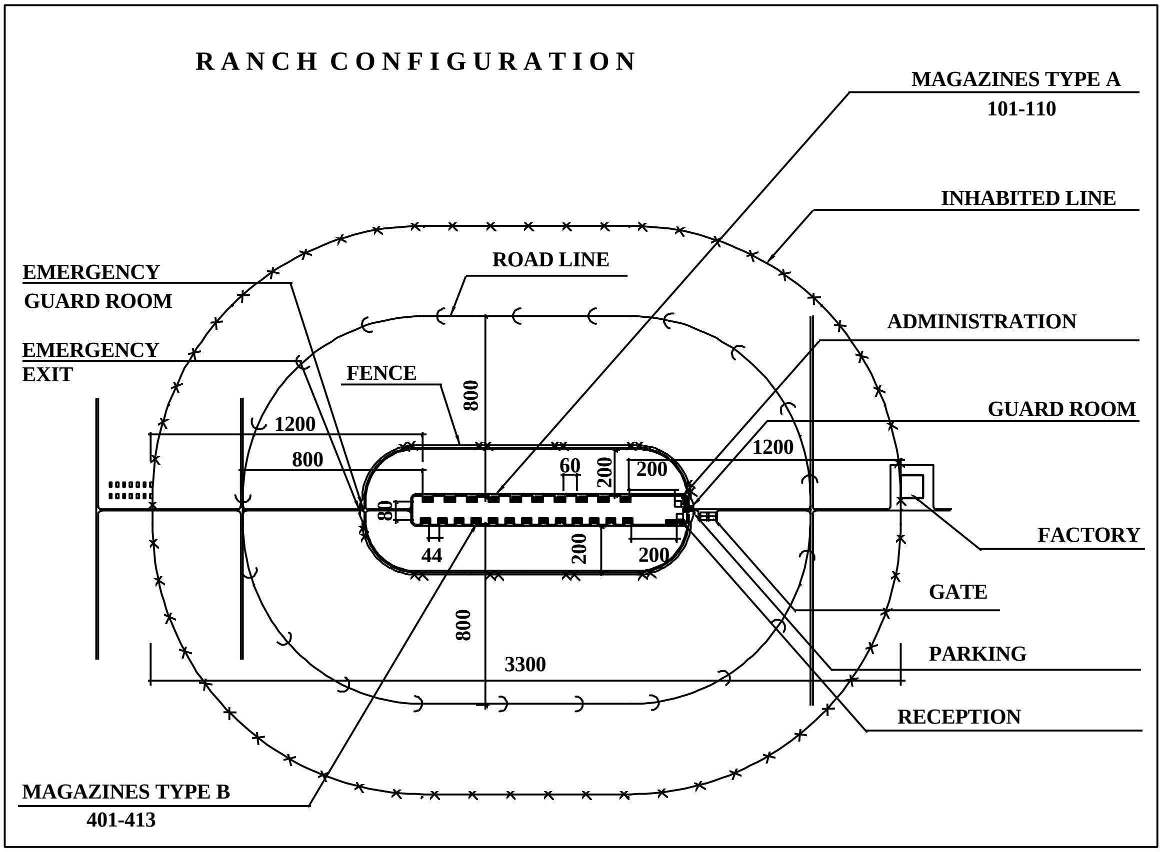

Figure 6: Configuration of ranch shown in the example

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